

(19)



(11) Publication number:

SG 173675 A1

(43) Publication date:

29.09.2011

(51) Int. Cl:

;

(12)

Patent Application

(21) Application number: **2011058336**

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(22) Date of filing: **12.03.2010**

(30) Priority: **US 12/404,158 13.03.2009**

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(54) Title:

GENERAL PURPOSE PROTOCOL ENGINE

(57) Abstract:

In one embodiment, a protocol engine circuit for automatic test equipment, which includes a protocol generation circuit constructed to retrieve protocol unique data and format the protocol unique data with a selected protocol definition corresponding to a device under test for testing the device under test. The protocol generation circuit may be constructed to retrieve the selected protocol definition from a protocol definition table.



(51) International Patent Classification:

G01R 31/28 (2006.01) G01R 19/00 (2006.01)
G01R 31/317 (2006.01)

(21) International Application Number:

PCT/US2010/027247

(22) International Filing Date:

12 March 2010 (12.03.2010)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

12/404,158 13 March 2009 (13.03.2009) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,

AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(88) Date of publication of the international search report:

13 January 2011

(54) Title: GENERAL PURPOSE PROTOCOL ENGINE

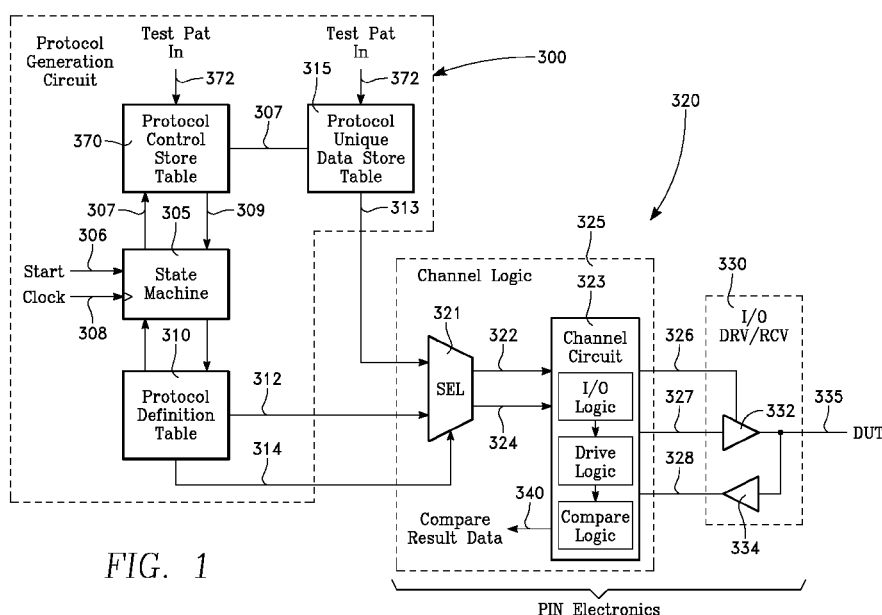


FIG. 1

(57) Abstract: In one embodiment, a protocol engine circuit for automatic test equipment, which includes a protocol generation circuit constructed to retrieve protocol unique data and format the protocol unique data with a selected protocol definition corresponding to a device under test for testing the device under test. The protocol generation circuit may be constructed to retrieve the selected protocol definition from a protocol definition table.

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GENERAL PURPOSE PROTOCOL ENGINE**BY**

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BACKGROUND

[001] Automated stored pattern functional testing affords a critical step in the production of integrated circuit (IC) devices to provide parametric and operational characterization of the devices. An automatic test equipment system includes test circuitry that is connected to a control computer or host computer. The control computer provides a user interface that accepts and stores functional test pattern data for activating the test circuitry to provide stimulus signals to a device under test and receives the response signals from the device under test. The response signals are evaluated to determine the parametric and operational characterization of the integrated circuit devices.

[002] The device under test (DUT) is mounted on a device interface board or DIB, which provides the physical interface for physical signals from and to the pin electronics. The test stimulus signals from the test circuitry are supplied through pin electronics to the device under test via the DIB. The test response signals from the device under test are transferred through DIB to the pin electronics and on to the test circuitry. The test stimulus signals and the test response signals are correlated by the test circuitry to determine whether the device under test has passed or failed the test.

[003] The stimulus signals generated by the test circuitry include data signals and clock signals to synchronize the stimulus input. The effectiveness of the test

depends on the accurate placement of these signals relative to one another. For example, several different signals, such as, clock, data, and enable signals are coordinated and triggered at appropriate times to ensure that meaningful data is acquired during the test process. Various integrated circuit functions have interface specifications that comply with fixed timing and data protocols. For instance, these protocols include an n-wire serial structured bus such as Ethernet Management Data Input/Output (MDIO), Universal Serial Bus (USB) or Inter-Integrated Circuit (I²C) Bus, a parallel communication bus such as General Purpose Input/Output (GPIO), a memory bus such as double data rate Dynamic Random Access Memory (DDR), and high speed communication channels such as High-Definition Multimedia Interface (HDMI).

[004] As described above, in recent years stored pattern functional testing has run into increasing difficulties with devices that do not behave deterministically. Presently, the level of integration and complexity of semiconductor processing is allowing for integrated circuit chips to effectively be a complete "system-on-a-chip" (SOC). A system-on-a-chip integrates all the functional circuit elements of a computer or other electronic system into a single integrated circuit (chip). These integrated circuit elements may be any combination of digital circuits, analog circuits, random access memory, mixed analog and digital signal circuits, and often include radio-frequency functions.

[005] A system-on-a-chip (SOC) provides multiple digital and analog integrated circuit functions incorporated on the same semiconductor substrate. An example of an SOC is a cellular telephone that incorporates not only cellular telephone receiving, processing, and transmitting functions,

but also photographic and video processing functions, audio digital signal processing and semiconductor memory circuits. Presently, in most SOC testing, the individual functions of an SOC are tested separately in multiple testing methods, such as by SCAN testing, Built-In-Self-Test (BIST), and functional testing. System Level Test typically employs custom circuitry and is generally only used for high average selling price low mix devices, such as microprocessors. A final system level test may be implemented on customized test apparatus created specifically for the testing of specific SOC devices such as microprocessors. Although it would be desirable to perform a System Level Test for other SOC devices, building custom functional test apparatuses for low average selling price SOCs is not cost effective.

[006] A difficulty in testing SOCs with automatic test circuitry is that the parametric and individual functional testing with the automatic test circuitry is a deterministic test operation. The test stimulus signals are applied with certain timing and structure, and the test response signals are expected to have a particular timing and structure. If the test response signals do not match the expected timing and structure for the given parameters, the SOC device under test is determined to have failed. The functions of the SOC device may operate with differing timing and clocking specifications and may operate asynchronously. An SOC device may be operational when the response test signals indicate otherwise, when the asynchronicity of the communicating functions cause the test response signals to appear incorrect.

[007] The current generation automated test equipment systems have very limited capability to deal with non-deterministic SOC devices other than to provide certain

latency factors. This causes the test engineer significant problems, in that the first prototyped devices, more than likely, will not work when the test stimulus signals are the simulation vectors used in the design verification. A series
5 of trial and error loops ensues in which the test engineer tries to move vectors around until he finds a passing arrangement. Due to the large volume of data involved and the need to re-simulate every trial, each loop may take days, the net result being months added to the test and evaluation phase
10 of a new SOC device.

[008] There have been attempts within present automatic test equipment systems to simulate the operating conditions of an SOC device under test. Because of the nondeterministic function of the asynchronous communication
15 between circuit functions, the normal operating environment of the functions can not be accurately recreated for the SOC device under test. Present automatic test equipment environments lack the ability to easily and accurately provide the nondeterministic electrical and timing conditions of the
20 normal operating environment of the SOC device under test. This lack of the nondeterministic electrical and timing conditions within automatic test equipment systems, further do not measure the margin of error for an SOC device under test with regard to its tolerance under varying operational
25 conditions that may be present in its normal operational environment. Therefore, what is needed is a protocol generation circuit or engine within automatic test equipment for generating stimulus signals and timings that comply with a specified device protocol expected by a device under test and
30 receiving response signals according to the timings that comply with the specified device protocol.

SUMMARY

[009] In one embodiment, a protocol engine circuit for automatic test equipment, which includes a protocol generation circuit constructed to retrieve protocol unique data and format the protocol unique data with a selected protocol definition corresponding to a device under test for testing the device under test. The protocol generation circuit may be constructed to retrieve the selected protocol definition from a protocol definition table.

[010] In one implementation, a method for generating signals and timings that comply with a specified device protocol for communication between automatic test equipment and a device under test, the method includes receiving fixed protocol data for the device under test, receiving protocol unique data; and assembling the fixed protocol data and the protocol unique data into the specified device protocol for testing the device under test. The implementation may further include receiving a protocol definition location number, selecting fixed protocol data for the specified device protocol from a table location indicated by the protocol definition location number, and supplying the fixed protocol data and the protocol unique data in the specified device protocol for testing a device under test. In some implementations, the method further includes receiving an operation code and retrieving action data from a table location corresponding with the operation code, and supplying the action data along with the fixed protocol data and the protocol unique data in the specified device protocol for testing a device under test. In other implementations, retrieving the fixed protocol data for the specified device protocol includes retrieving action data, and supplying the fixed protocol data includes supplying the action data.

BRIEF DESCRIPTION OF THE DRAWINGS

[011] **FIG. 1** is a simplified block diagram of an embodiment of a protocol generation circuit.

[012] **FIG. 2** is a simplified block diagram of another
5 embodiment of a protocol generation circuit.

[013] **FIG. 3** is a table of exemplary operational actions for construction of a specified device protocol within one embodiment of an automatic test system.

[014] **FIGS. 4A and 4B** are more detailed block
10 diagrams of still another embodiment of a protocol generation circuit.

[015] **FIG. 5** is a block diagram of an automatic test equipment system incorporating multiple instances of one of the embodiments of the protocol specific circuits
15 incorporating the protocol generation circuit of **FIGS. 1, 2, or 4A and 4B.**

[016] **FIG. 6** is a diagram describing the relative structure and timing of the signals that comply with the Ethernet Management Data Input/Output (MDIO) protocol
20 specification.

[017] **FIG. 7** is a table of example operation codes.

DESCRIPTION

[018] A protocol specific circuit containing the particular protocol(s) for a specific SOC stored in an FPGA may be utilized to improve testing. Such an approach, however, could be too time consuming or limiting in some applications. Different SOC's, may require one or more different protocols. Various SOC's may include one or more of an n-wire serial structured bus such as Ethernet Management Data Input/Output (MDIO), Universal Serial Bus (USB) or Inter-Integrated Circuit (I²C) Bus, a parallel communication bus such as General Purpose Input/Output (GPIO), a Memory such as double rate Dynamic Access Memory (DDR), and high speed communication channels such as High-Definition Multimedia Interface (HDMI), or others. An advantage of a tester that is capable of generating a large number of different protocols for various DUT's is that it can increase tester functionality and improve test efficiency.

[019] **FIG. 1** is a simplified block diagram of an embodiment of a protocol generation circuit **300** and its interconnection with the pin electronics **320**. The test pattern commands **372** may be input to a host device, stored in a Dynamic Random Access Memory (DRAM) (not shown), and transferred to the protocol control storage table **370**. The protocol control storage table **370** stores the Opcodes that define the commands for constructing the stimulus signals and timings that comply with a specified device protocol. The Opcodes may be decoded, or partially decoded, or structured to directly provide the control signals for generating the stimulus signals and timings that comply with a specified device protocol. The Opcodes are transferred to the transaction state machine **305** through connection **309**. At the activation of the Start signal **306**, the transaction state

machine **305** provides a series of timing cycles which define execution order of the operational actions of the specified device protocol based on the operation code as synchronized by the clock **308**. The timing cycle signals are transferred to the protocol definition table **310**. Timing signals **307** also are transferred from the transaction state machine **305** to the protocol control storage table **370**, to increment the transmission of the Opcodes **302** (shown in **FIG. 2**) and table number **304** (shown in **FIG. 2**). The timing signals **307** also are transferred to the protocol unique data storage table **315** to increment the transmission of the expect data **317** and drive data **319**.

[020] The test pattern commands **372** also contain a protocol definition location number which defines the location within the protocol definition table **310** that contains the set of fixed protocol data, which may in some embodiments further include corresponding action signals for the specified device. In other embodiments, discussed below with reference to **FIG. 2**, the actions signals may be contained in a separate action table **350**.

[021] Referring to **FIG. 1**, the protocol engine test pattern commands **372** also contains the protocol unique data that is to be used for each of the transactions to be executed. The protocol unique data is placed in the protocol unique data storage table **315**. The protocol unique data may be the data to be driven as stimulus signals to the device under test **335**, expected data to be compared with the response signals from the device under test, or masking data used for the control of the flow of data during the execution of the transactions.

[022] The pin electronics **320**, as shown, includes the channel logic **325** and the I/O drivers **330**. The channel logic

includes a selector **321** and the channel circuit **323**. The selector **321** receives the fixed protocol data **312** from the protocol definition table **310**, and the protocol unique data **313** from the protocol unique data storage table **315**. The action signals **314** from the protocol definition table **310** provide the control instructions for selecting whether the fixed protocol data **312** or the protocol unique data **313** are transferred to as selected data signals **322** or the command signals **324** are transferred to the channel circuit **323** to appropriately activate the channel circuit **323**. The drive data output **327** of the channel circuit **323** is the input to the driver **332** of the I/O Driver/Receiver **330** of the pin electronics **320** to provide the protocol unique data **313** or the fixed protocol data **312** that is to be driven if the automatic test equipment is driving stimulus data to the device under test **335** according to the specified device protocol. Alternately, the Control output **326** of the channel circuit **323** provides the necessary control signal to the driver **332** to deactivate the driver **332** when the automatic test equipment is receiving response signals from the device under test **335**. The receiver **334** is connected to receive the response signals from the device under test. The receiver **334** is connected to transfer the received data **328** to the channel circuit **323**. The channel circuit **323** receives the expected protocol unique data **313** from the protocol unique data storage table **315** and the expected fixed protocol data **312** from the protocol definition table **310**. The expected protocol unique data **313** and the fixed protocol data **312** are compared with the response signals from the receiver **334** to determine whether the device under test **335** is functioning correctly. The channel circuit **323** provides a compare result signal **340** that is transferred to a failure processor (not shown).

[023] **FIG. 2** is a simplified block diagram of another embodiment of a protocol generation circuit **370** and its connectivity to the pin electronic **320**. The structure of this embodiment of a protocol generation circuit **370** is similar to that described above for **FIG. 1**. The protocol control storage table **370** includes a First-In-First-Out (FIFO) memory **301** that acts as a high speed buffer for the Opcodes. The output of the FIFO **301** is transmitted to state flip-flop **302**. The protocol control storage table **370** transmits the Opcodes **309a** on the connection to the transaction state machine **305** and the action table **350**. As described above, the transaction state machine **305** provides a series of timing cycles which define the execution order of the operational actions of the specified device protocol based on the operation code as synchronized by the clock **308**, at the activation of the Start signal **306**.

[024] The protocol control storage table **370** also includes a FIFO memory **303** that acts as a high speed buffer for the protocol definition location numbers. The output of the FIFO **303** is transmitted to table number state flip-flop **304**. The table number state flip-flop **304** transmits the protocol definition location number on the connection **309b** to the transaction state machine **305** which are then passed through the connection **311** to the protocol definition table **360** to provide the location within the protocol definition table **360** that contains the set of fixed protocol data **362** for constructing the data and timings of the specified device protocol.

[025] The protocol unique data storage table **315** includes a FIFO memory **316** that acts as a high speed buffer for the expected data to be compared with the response signals from the device under test. The output of the FIFO **316** is

transmitted to state flip-flop **317**. The state flip-flop **317** transmits the expected data on the connection **313a** to the compare logic **356** of the channel logic **325**. Similarly, the protocol unique data storage table **315** includes a FIFO memory **318** that acts as a high speed buffer for the protocol unique data that is to be driven to the device under test according to the specified device protocol. The output of the FIFO **318** is transmitted to state flip-flop **319**. The state flip-flop **319** transmits the drive data on the connection **313b** to the drive logic **354** of the channel logic **325**.

[026] In this embodiment, separate protocol definition and action tables **360** and **350**, respectively, are provided. This is to make use of the fact that in some embodiments, for any given protocol there is a subset of actions that can take place for each bit time. **FIG. 3** is a table of example operational actions which may be used for construction of a specified device protocol within an automatic test equipment system. These actions may include Drive 0 or Drive Data, Hold if Lo, Proceed on Change, or Pulse Lo-Z if H. **FIG. 3** is an example list, others actions are possible. Any additional actions may be added to the list and the protocol generation engine **370** updated to accommodate them. In some embodiments there are only a limited number of drive actions, a limited number of compare actions, and a limited number of I/O actions that can take place for each bit time. The protocol definition table **360** stores fixed protocol data and the action table **350** stores the actions corresponding to the Opcodes **309a**. The Opcodes **309a** and the fixed protocol data **362** provide pointers to the locations in the action table **350** that select the signals for guiding the selected data signals **322a** and **322b**, and the command signals **324** to appropriately activate the channel logic **325**. The output **322a**

of the action table **350** guides the fixed protocol data **362** from the protocol definition table **360** to the drive logic **354** within the channel logic **325**. Similarly, the output **313b** of the drive data state flip-flop **319** provides the protocol
5 unique data **313a and 313b** to the drive logic **354**. The drive logic **354** provides the stimulus data to the driver **332** and thus to the device under test **335**.

[027] The output **322b** of the action table **350** guides the fixed protocol data **362** from the protocol definition table
10 **360** to the compare logic **356** within the channel logic **325**. Similarly, the output **313a** of the expected data state flip-flop **317** provides the expected protocol unique data **313a** to the compare logic **356**. The compare logic **356** receives the response data from the device under test **335** through the
15 receiver **334**. The compare logic **356** provides a compare result signal **340** that is transferred to the transaction state machine **305** and a failure processor (not shown).

[028] The output of the action table **350** contains the action signals **324** to the I/O logic **352** of the channel logic
20 **325**. The I/O logic **352** activates the appropriate controls of the drive logic **354**, the compare logic **356**, and the driver **332** of the I/O Driver/receiver **330** to generate the appropriate transaction, bit by bit for determining the operational status of the device under test **335**.

[029] **FIGS. 4A and 4B** are more detailed block diagrams of still another embodiment of a protocol generation circuit **370** with its interconnection to the pin electronics
25 **320**. The source data storage concept of the protocol generation circuit **370** within automatic test equipment of this embodiment is to store as little information as possible in Dynamic Random Access Memory (DRAM) (not shown). This means that only Opcode, table number and payload bits (data bits)
30

are to be stored in the DRAM (not shown). All constant protocol specific bits (like start/stop bits or care bits) are stored in the protocol definition table **410** and thus take no space in DRAM (not shown). The DRAM (not shown) provides test pattern data for the Opcode **372a**, for the table number **372b**, the drive data **372c**, expect data **372d** and the masking data **372e**. The Opcode **372a** and the table number **372b** are the inputs to the protocol control storage table **400**. The drive data **372c**, the expected data **372d**, and the data mask bits **372e** are the inputs to the protocol unique data storage table **415**.

[030] The loading sequence proceeds once the protocol execution state machine **405** issues a Next command **409**. An Opcode is clocked into the Opcode state flip-flop **402** and a table number is clocked into the table location state flip-flop **404**. The Opcode is decoded sufficiently to determine if this is a read, write or mask update transaction. The drive data **372c**, expect data **372d** and data mask **372e** sizes are looked up in a small RAM. The protocol execution state machine **405** then loads the proper number of into block Random Access Memories (RAMs) that are used in this case as FIFO's (not shown). The outputs of the FIFO's are the inputs to the drive data flip-flop **416**, the expected data flip-flop **417**, and the data mask flip-flop **418**.

[031] The drive data flip-flop **416**, the expected data flip-flop **417**, and the data mask flip-flop **418** are used by the protocol execution state machine **405** to service protocols with varying data width requirements all the way from a single serial stream to multiple bit wide busses. Further, multiple protocol generation circuits may be grouped to service wider busses. The bit swizzle of the drive data flip-flop **416**, the expected data flip-flop **417**, and the data mask flip-flop **418**

will be programmed at start of a burst to convert a number of the bits out of the RAM into 1, 2, 4 or any number of bits to the protocol execution state machine **405** as required by the protocol.

5 [032] The enable lines of the drive data flip-flop **416**, the expected data flip-flop **417**, and the data mask flip-flop **418** indicate that the next set of data should be output on the next bit clock. The reset line is used in the special case of a wait until or Repeat Opcode. In this case, if the
10 condition has not been met (Transaction Reject has occurred or Repeat not done), the transaction needs to be repeated. A Last Bit signal without a Next Command **409** means that the FIFO's should reset the memory pointer to repeat the transaction.

15 [033] The output of the protocol control storage table **400** and the protocol unique data storage table **415** will then have the Opcode, protocol definition location number, drive data **413a**, expect data **413b** and data mask bits **413c** all properly aligned at the start of the next transaction. The
20 Opcode state flip-flop **402** is a multiple output register containing the decoded or partially decoded Opcode. One set of the outputs of the Opcode state flip-flop **402** provides an initial definition code **403a** to the protocol execution state machine **405** for initializing the protocol execution state
25 machine **405** state counter. A portion of the Opcode is a read/write transaction bit **403b** is then transferred from the Opcode state flip-flop **402** to the protocol definition tables **410**. The transaction definition **403c** is transferred from Opcode state flip-flop **402** to the action table **450**. A
30 transaction offset portion **403d** of the Opcode is combined with the table location **401** from the table location state flip-flop **404** in the table offset calculator **406** to generate the exact

offset location from the beginning pointer of the table location **401** for each transaction being executed. The table location bits **491** from the protocol execution state machine **405** are combined with the output of the offset calculator **406** in the adder **407** to determine the exact location within the protocol definition table **410** the definition and the fixed data for the next transaction.

[034] This embodiment of the protocol generation circuit **370** is structured for controlling multiple channels of the automatic test equipment to stimulate multiple pins of the device under test **435**. To accomplish this, the protocol definition table **410** includes multiple definition table RAM's **461**, **462**, **463**, and **464** and separate action tables **450**. The multiple definition table RAM's **461**, **462**, **463**, and **464** communicate through separate action tables **450** to the channel logic circuitries **425** and the I/O Driver/Receiver **430** of the pin electronics **320** to separate pins of the device under test **435**. In automatic test equipment incorporating this embodiment of the protocol generation circuit **370**, the protocol generation circuit **370** supports eight channels communicating with eight pins of the device under test **435**. Multiple protocol generation circuits **370** are optionally ganged together to support wider bus widths for instance a 64bit bus. The ganged protocol generation circuits **370** would execute identical Opcodes. The multiple definition table RAM's **461**, **462**, **463**, and **464** would contain different definition signals for signals to be applied to the pins of the device under test based on the function for each of the pins.

[035] The table offset calculator **406** and Adder **407** generate an offset address for the transaction definition address as different multiple definition table RAM's **461**, **462**,

463, and **464** are executed. Each new transaction for both read and write may have different lengths and different definitions. The table offset calculator **406** and Adder **407** are programmed with the offset for each transaction type. This allows many short transaction types or fewer long ones within the multiple definition table RAM's **461**, **462**, **463**, and **464** as long as the total length of all transactions does not exceed the available storage space in the multiple definition table RAM's **461**, **462**, **463**, and **464**.

[036] The protocol definition table **410** includes a protocol definition control table **461** that provides additional bits (3 bits for this implementation) for general housekeeping functions. The bits are defined as Last bit **492a**, Store **492b**, and Invert Hold Sense **492c**. The Last Bit informs the protocol execution state machine **405** that the last bit of a transaction is transmitted. The protocol execution state machine **405** issues a Next command. The Next Command is issued if the following transaction is not being held, a repeat count is reached, there are no wait conditions, or it can repeat the previous transaction. The Store defines which cycles are store cycles. The actual bits to be stored are defined before the burst by the setup of the Capture Logic **475**. The Invert Hold Sense inverts the sense of the Hold line **493**. The function of the Hold line **493** is explained hereinafter.

[037] The outputs **412a**, **412b**, ... **412x** of the multiple protocol definition table RAM's **462**, **463**, and **464** are applied to their individual action tables **450**. The action table **450**, mainly gets its address from the protocol definition table RAM **462**, but a certain number (i.e. 2) of the address bits **403c** come from Opcode state flip-flop **402**. This is to handle cases in which the Opcode changes the action of certain bits of the transaction, for example Read and Mask Read. In alternate

embodiments the changes in the actions could be handled by adding transaction types to the protocol definition table RAM **462**. However, the protocol definition table RAM **462** is relatively expensive versus the action table **450**, thus making the address bits **403c** a more desirable implementation.

[038] The fixed protocol data signals **422a** and the transaction command signals **424a** from the outputs of the action table **450** are the inputs to the channel logic **425**. The command signals **424a** include the Hold signal that indicates that one of the hold actions is being executed and the condition has not been met. A pulse time signal in the command signals **424a** is a timed pulse used by the pulse generator **458** to generate clock pulses for the device under test **435**. An enable mask in the command signals **424a** allows the reading of the mask bit from the data mask flip-flop **418**. The fixed protocol data **412a** is stored to the protocol definition table **462** and transmitted to the action table **450** for decoding to generate the fixed protocol data **422a**. The fixed protocol data **422a** is transmitted to the channel logic **425**. The protocol unique data **413a** is transmitted from the drive data flip-flop **416** to the channel logic **425**. The data masking bit **413c** is transmitted from the data mask flip-flop **418** to the channel logic **425**. A function select bit of the command signals **424a** select the source of the data to be transmitted to the pin of the device under test **435**. The output of the drive logic **452** is the input of the pin driver **432** of the I/O Driver/Receiver **430**.

[039] The command signals **424b** are the inputs to the I/O logic **454**. The I/O logic **454** controls the pin driver **432**. When the pin driver **432** is actively driving data the I/O logic **454** sets the impedance control to allow the driving. Alternately, the I/O logic **454** allows the pin driver **432** to

switch between a high impedance state or driving to a Lo state based on a timed pulse. The high impedance state allows the receiver **434** of the pin electronics **430** to receive data from the device under test **435**. Alternately, some protocols have
5 special coding where clock lines are pulled low for signaling purposes (i.e. I²C). The impedance control facilitates these functions.

[040] The output of the receiver **434** is the input to the compare logic **456**. The compare logic **456** implements the
10 Compare Actions of **FIG. 3**. The compare logic **456** compares response data from the device under test **435** as acquired by the receiver **434** with expected data **413b** from the expected data state flip-flop **417**. Additionally the compare logic **456** receives the data mask bits **412c** from the data mask flip-flop
15 **418**. The results of the comparison of the response data and the expected data **413b** and the data mask bits **412c** determine if the transaction has failed. Further the compare logic **456** manages the various hold conditions for the flow control of the protocol generation circuit **370**.

[041] As part of the flow control of the protocol generation circuit **370**, the round trip FIFO **485** delays the
20 expected response data **413b** and data mask bits **413c** to move them later in time by the round trip time through the device under test **435**. The delay allows the compare logic **456** to
25 compare the response data from the device under test **435** with the one of the drive data **413a**, expected response data **413b** and data mask bits **413c**. Additionally, the round trip FIFO **485** delays the transaction table number **423** from the action table **450** for alignment with the compare result data **459** in
30 the capture logic **475**. The round trip FIFO **485** delays the expected fixed data signals **422b** for comparison in the compare logic **456** with the response data from the receiver **434**.

[042] The next function of the flow control of the protocol generation circuit **370** is the Hold OR tree **465**. The Hold OR tree **465** receives Hold and Enable signals from the I/O Logic **454** and the compare logic **456** of each of the channels being grouped for the protocol being emulated by the protocol generation circuit **370** or groups of ganged protocol generation circuits **370**. The Hold output **493** of the Hold OR tree **465** is transferred to the protocol execution state machine **405** and the capture logic **475** to insure proper flow of the protocol being emulated in the testing of the device under test **435**. The loop time from action table **450** output to device under test **435** and back then through the Hold OR tree **465** to the protocol execution state machine **405** sets the maximum device under test frequency.

[043] One of the outputs of the compare logic **456** is the transaction reject signal **457** that is transferred to the transaction reject OR tree **470**. The transaction reject signal **457** provides a signal that the device under test **435** has failed at one or more of the transactions occurring at a particular bit transaction time. All the transaction reject signals **457** of each of the channels being grouped for the protocol being emulated by the protocol generation circuit **370** or groups of ganged protocol generation circuits **370** are the inputs to the transaction reject OR tree **470**. The output **494** of the transaction reject OR tree **470** is an input to the protocol execution state machine **405** to provide condition indications of the progress of the generation of the protocol for testing the device under test **435**.

[044] The capture logic **475** receives the compare result data signal **459** from the compare logic **456** describing the state of the comparison of the response data from the device under test **435** with the expected data **413b**. The

compare logic also receives the delayed transaction table number **486a** and the delayed store signal **486b** from the round trip FIFO **485**. The capture logic **475** captures the read data from the compare result data signal **459** for use at a later time for Read/Modify/Write operations. The capture logic **475** stores the compare result data signal **459** with a timestamp and the table number **486a** for correlation with data with other protocol generation circuits **370**. The compare result data signal **459** with a timestamp and the table number **486a** is transferred to the DRAM **220**.

[045] As described above, the protocol execution state machine **405** provides a series of timing cycles which define the operational actions of the specified device protocol based on the Opcode as synchronized by the clock **408**. The timing cycle signals are transferred to the protocol definition table **410**. The table location bits **491** are transferred from the protocol execution state machine **405** to adder **407** and thus to the protocol definition table **410** for accessing the transaction data for forming the protocol for generating the stimulus signals to be sent to the device under test and receiving and evaluating the response from the device under test.

[046] Other functions of the protocol execution state machine **405** include providing flags **497** that are used to communicate with the Host. The protocol execution state machine **405** can set or compare to any combination of a limited number of flags. The operand of the flag **497** will contain mask bits, write bits or compare flags. In the case that multiple protocol generation circuits **370** are ganged, only one protocol execution state machine **405** is used for Flags and the other protocol execution state machines **405** will receive status from the master unit.

[047] The latency synchronization signal line (ISL) **498** is used by the master protocol execution state machine **405** for dispatching the initiation of a particular protocol action across protocol execution state machines **405**.

5 [048] **FIG. 5** is a block diagram of an automatic test equipment system **500** incorporating multiple instances of one of the embodiments of the protocol specific circuits **505a, ..., 505n** incorporating the protocol generation control **370** of **FIGS. 1, 2, or 4A and 4B**. The automated test equipment system
10 **500** has multiple channels of the protocol specific circuits **505a, ..., 505n** that are connected to multiple pin electronic units **510a, ..., 510n**. Each of the multiple pin electronic units **510a, ..., 510n** as described above provide the electrical interface **502a, ..., 502n** and **504a, ..., 504n** between the SOC
15 device under test **540** and the automated test equipment system **500** through the physical interconnections of the load adapter. Each of the protocol specific circuits **505a, ..., 505n** is connected to at least one of the multiple pin electronic units **510a, ..., 510n** to provide the test stimulus signals to and
20 receive the test response signals from the SOC device under test **540**.

[049] Each of the protocol specific circuits **505a, ..., 505n** has a protocol generation circuit **370** that functions as those described in **FIGS. 1, 2, or 4A and 4B**, in coordination
25 with the remaining circuitry of the protocol generation circuit **370**. Each protocol generation circuit **370** of the protocol specific circuits **505a, ..., 505n** communicates with its designated DRAM **520a, ..., 520n** to provide the test commands and to log the test results of the exercising of the SOC device
30 under test **540**.

[050] In protocols that have a large number of pins, the protocol specific circuits **505a, ..., 505n** coordinate the

decoding of the commands and generate the test response signals that simulate the expected responses synchronously. To simulate the expected responses synchronously, the protocol specific circuits **505a**, ..., **505n** communicate through a synchronization communication interface **525** between those of the protocol specific circuits **505a**, ..., **505n** that may cooperate. The synchronization communication interface **525** contains the transaction rejection signals from the transaction reject OR tree and the HOLD signals from the Hold Or tree. This cooperation may effect the latency of the operation and thus the communication is structured to minimize the impact of the cross communication between the protocol specific circuits **505a**, ..., **505n**. For instance one of the state machines (not shown in **FIG. 5**) for the protocol generation circuits **505a**, ..., **505n** may act as a master and receive the test stimulus signals directly from adjacent protocol specific circuits **505a**, ..., **505n** for decoding. The master protocol engine controller (not shown) then dispatches the appropriate instructions for constructing the structure and timing of the test response signals specified by the protocol, while minimizing the impact of the latency for the operation. The latency synchronization signal line (ISL) **535** is used by the master protocol engine controller (not shown) for dispatching the initiation of a particular protocol action across multiple protocol specific circuits **505a**, ..., **505n**.

[051] The automated test equipment system **500** may have multiple master oscillators **530a** and **530b** to generate the different timings determined by the protocol specific circuits **505a**, ..., **505n**. This is true especially for the deterministic operation of the automated test equipment system **500**. In the non-deterministic operation of the automated test equipment system **500**, the master oscillators **530a** and **530b** may be used

for those portions of the testing involving deterministic operation while an exterior timing from the SOC device under test **540** may be used for the protocol engine controller (not shown) in non-deterministic operation.

5 [052] Refer now to **FIG. 6** for an example diagram describing the signals and timings that comply with the Ethernet Management Data Input/Output (MDIO) protocol specification. The MDIO is a two pin serial bus protocol where one station on the bus acts as a master and all others
10 on the bus act as slaves. The master generates a clocking signal for the bus and the operations as transmitted by the master are a READ operation and a WRITE operation. The beginning of each packet of the protocol begins with a preamble **652** followed by a start of frame **653** and an operation
15 code **654**. The fixed data **650** includes each of these codes and are defined to be stored in the protocol definition table. Even though there are separate operation codes, there are only two codes to define the operation codes. Placing them in the protocol definition table allows savings within the test
20 patterns. The physical address **657** and the destination address **658** are generated with execution of the test pattern to generate the protocol and therefore unique drive and expected data **655** stored in the unique drive data FIFO. The turn around time bits **660** are dependent on the type of
25 transaction being performed, however, they have few combinations and would be considered fixed data and stored in the protocol definition table. The address/data bits **665** are unique drive data to be stored in the unique drive data FIFO. The idle time bit times **670** actually provide a command that
30 would be set to force the driver of the pin electronics to a high impedance state.

[053] **FIG. 7** is a table of exemplary Opcodes developed from the operational actions for definition of a specified device protocol. The Opcodes are now a "shorthand" command language that instructs a protocol generation circuit within automatic test equipment the timing and signals for each pin to execute the protocol. The Opcodes of this example are the transaction definitions for generating the timing and data structure of the protocol. The example Opcode definitions also include Engine Update Opcodes for the Host of the automatic test equipment to provide direct instructions for the protocol generation circuit. The Flow control Opcodes provide communication between groups of ganged protocol generation circuits, test pattern generator or the Host of the automatic test equipment in order to control test pattern flow.

[054] The protocol generation circuit makes use of the fact that for any given protocol there are only a small set of actions, for example as shown in **FIG. 3**, that can take place for each bit time. From these actions, it is possible to assemble a series of the actions for each pin of a protocol and thereby generate the protocol. This string of actions is contained in the protocol definition table. The actions are structured as a set of Opcodes that define the type of transaction: read, write, read until, etc. The table number within the protocol definition table informs the state machine which of multiple transaction definitions apply for this particular transaction. The expected response data is the unique data contained in a read transaction from the automatic test equipment perspective. The drive stimulus data is the unique data for both write and read transactions (there could be unique drive data in a read transaction: for example, address). A protocol execution state machine retrieves the

protocol definition for the transaction selected by Opcode and table number; the Opcode is decoded in the action table into specific enable bits; these enable bits are combined with the drive stimulus and expected response data in the channel logic to generate the appropriate transaction, bit by bit. When the transaction is complete, the protocol execution state machine advances to the next Opcode, table number and Data. Protocols wider than a single bit are generated by duplicating the protocol generation circuits over the multiple bits.

[055] Referring to **FIGS. 1 and 2**, in one embodiment, the protocol control definition table **310** or **360** provides a protocol definition storage means. The protocol control storage table **370** provides a means for selecting and retrieving a protocol definition from the protocol definition storage table **360**. The protocol unique data storage table **315** is a means to deliver test data for testing the DUT. In some embodiments, the action table **350** may be provided to use the selected protocol definition as part of the means to provide the test data for testing the DUT.

[056] As is understood by a person skilled in the art, a program storage device can be created that contains reconfiguration instruction code that is executable on a computing device coupled to a reconfigurable integrated circuit such as a field programmable gate array. The reconfiguration instruction code when executed configures internal circuitry of the reconfigurable integrated circuit to form a protocol generation circuit as described in **FIGS. 1, 2, or 4A and 4B**. The reconfigurable integrated circuit, as configured, performs a process for generating signals and timings that comply with a specified device protocol for communication between automatic test equipment and a device under test.

[057] It is understood that the term "table" as used herein may include a memory storage device containing stored and retrievable information, or other devices capable of such.

[058] While this invention has been particularly
5 shown and described with reference to the embodiments thereof,
it will be understood by those skilled in the art that various
changes in form and details may be made without departing from
the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A protocol engine circuit for automatic test equipment, the protocol engine circuit comprising a protocol generation circuit constructed to retrieve protocol unique
5 data and format the protocol unique data with a selected protocol definition corresponding to a device under test for testing the device under test.

2. The protocol engine circuit of claim 1, further comprising a protocol definition table, wherein the protocol
10 generation circuit is constructed to retrieve the selected protocol definition from the protocol definition table.

3. The protocol engine circuit of claim 2, wherein the protocol generation circuit comprises a protocol control circuit.

15 4. The protocol engine circuit of claim 3, wherein the protocol control circuit comprises a protocol control storage table in communication with a host device for receiving and storing an operation code and a protocol definition location number.

20 5. The protocol engine circuit of claim 4, wherein the protocol generation circuit further comprises an action table connected to receive fixed protocol data from the protocol definition table and operation codes from the protocol control storage table to generate fixed protocol data including action
25 signal data for testing the device under test.

6. The protocol engine circuit of claim 4, wherein the protocol generation circuit comprises a protocol unique data storage table.

7. The protocol engine circuit of claim 6, wherein the
30 protocol unique data storage table comprises:

a) a drive data table containing the protocol unique data for the device under test; and

b) an expected data table containing the protocol unique data expected as a response from the device under test.

8. The protocol engine circuit of claim 6, wherein the protocol generation circuit comprises a transaction state machine in communication with the protocol control storage table to provide a series of timing cycles used to define the operational actions of a specified device protocol based on the operation code.

9. The protocol engine circuit of claim 8, wherein the protocol control storage table comprises:

a) an operation code storage device for storing the operation codes and transferring the operation codes in a sequential order to the transaction state machine; and

b) a transaction location storage device for storing the protocol definition location number and transferring the protocol definition location number to the transaction state machine.

10. The protocol engine circuit of claim 9, wherein the protocol generation circuit further comprises an action table connected to receive fixed protocol data from the protocol definition table and operation codes from the protocol control storage table to generate fixed protocol data including action signal data for testing the device under test.

11. The protocol engine circuit of claim 10, wherein the operation code includes instructions for managing command and control between the protocol engine circuit and the host device.

12. The protocol engine circuit of claim 11 further comprising flow control circuits, and wherein the operation code includes instructions for managing flow control between a plurality of protocol engine circuits.

13. The protocol engine circuit of claim 2, wherein the

protocol definition table includes action signal data.

14. The protocol engine circuit of claim 1, further comprising a protocol definition table comprising a plurality of protocol definitions for the device under test.

5 15. The protocol engine circuit of claim 1, further comprising a protocol definition table comprising a plurality of protocol definitions for a plurality of devices under test.

16. A protocol engine circuit for automatic test equipment, the protocol engine circuit comprising:

- 10 a) a protocol control storage table in communication with a host device for receiving and storing a test pattern including an operation code and a protocol definition location number;
- b) a transaction state machine in communication
15 with the protocol control storage table to provide a series of timing cycles which define the operational actions of a specified device protocol based on the operation code;
- c) a protocol definition table responsive to the transaction state machine for supplying fixed protocol data
20 for a device under test corresponding to the protocol definition location number;
- d) an action table responsive to the transaction state machine to provide action data corresponding with the operation code; and
- 25 e) a protocol unique data storage table in communication with the host device for receiving and storing a test pattern including expected data and drive data, the protocol unique data storage table being responsive to the series of timing cycles to supply protocol unique data
30 corresponding with the fixed protocol data and action data to a pin electronic circuit for testing the device under test.

17. A method for generating signals and timings that

comply with a specified device protocol for communication between automatic test equipment and a device under test, the method comprising:

- a) receiving fixed protocol data for the device under test;
- b) receiving protocol unique data; and
- c) assembling the fixed protocol data and the protocol unique data into the specified device protocol for testing the device under test.

10 18. The method of claim 17, further comprising:

- a) receiving a protocol definition location number;
- b) selecting fixed protocol data for the specified device protocol from a table location indicated by the protocol definition location number; and
- c) testing the device under test using the fixed protocol data and the protocol unique data in the specified device protocol.

19. The method of Claim 18 further comprising receiving an operation code and retrieving action data from a table location corresponding with the operation code, and supplying the action data along with the fixed protocol data and the protocol unique data in the specified device protocol for testing a device under test.

20 20. The method of Claim 18, wherein retrieving the fixed protocol data for the specified device protocol includes retrieving action data, and wherein testing comprises using the action data.

21. The method of claim 18 further comprising storing and supplying protocol definition location numbers, operation codes, and protocol unique data in a sequential order.

22. The method of claim 18, wherein receiving the

protocol definition location number and retrieving the fixed protocol data comprises using a state machine.

23. The method of claim 22, wherein receiving the protocol definition location number comprises receiving the protocol definition location number from a protocol control storage table and further comprising using the state machine to select the fixed protocol definition from a protocol definition table.

24. The method of claim 23, further comprising using the state machine to receive an operation code from the protocol control storage table and selecting action data from an action table corresponding to the operation code from the protocol control storage table.

25. The method of claim 24, wherein testing comprises supplying the protocol unique data from a protocol unique data storage table.

26. The method of claim 25 further comprising supplying the fixed protocol data, the action data, and the protocol unique data to pin electronics logic circuits.

27. The method of claim 26 further comprising loading test pattern commands into the protocol control storage table and the protocol unique data storage table.

28. The method of claim 18, wherein receiving the protocol definition location comprises receiving the protocol definition location number from a host device.

29. A general purpose protocol engine comprising:

a) a protocol definition storage means comprising a protocol definition for a DUT.

b) a means for selecting and retrieving a protocol definition from the protocol definition storage means; and

c) a means for providing test data using the protocol definition for testing a DUT.

30. The general purpose protocol engine of claim 29, wherein the protocol definition storage means comprises a protocol definition table comprising the protocol definition required to functionally test the DUT.

5 31. The general purpose protocol engine of claim 30, wherein the means for providing test data comprises a data storage table and an action table.

10 32. The general purpose protocol engine of claim 29, wherein the means for selecting and retrieving the protocol definition from the group of stored protocol definitions comprises a protocol control storage table and a protocol definition table, and wherein the means for providing test data with a selected protocol comprises a data storage table and a selector.